4. GROUNDWATER MODEL DEVELOPMENT

As part of the Groundwater Management Plan (GWMP), hydrogeologic data was collected and a groundwater model was developed. This section describes the basis for the development of the groundwater model and the software used.

4.1 SOFTWARE APPLICATION

Groundwater Modeling System (GMS) Version 5.1 was used to develop the GWMP model. GMS is a popular groundwater software application developed at Brigham Young University and is used as a pre- and post-processor for the U.S. Geological Survey groundwater flow model, MODFLOW-2000 (Harbaugh, et.al., 2000). MODFLOW is the most widely used groundwater flow code in use today, capable of simulating the primary aquifer flow processes such as pumping from wells, interaction between the aquifer and streams, and recharge. GMS offers a variety of tools that expedite the development of groundwater models and the analysis of the results in order to meet the overall schedule of the project.

MODFLOW was developed to simulate the movement of groundwater through porous earth materials such as unconsolidated sands and gravels. The simulation of groundwater flow through fractured bedrock is more complex. Because there are no widely used groundwater models to simulate flow through fractured rock, it is common to use MODFLOW for this purpose. MODFLOW gives estimates of the bulk movement of groundwater through bedrock, but does not simulate the complex flowpaths of groundwater through individual fractures on a smaller scale.

4.2 MODEL GRID AND BOUNDARY CONDITIONS

The boundaries of the model were chosen based on the conceptual model to maintain a manageable model size, visually display the selection of boundary conditions, and minimize the effect of boundary condition assumptions in the study area. It is common practice to extend the boundaries of a groundwater model to the location of an impermeable material, a large body of surface water, or a watershed divide. This model would have become large and unmanageable if extended to a watershed divide or an impermeable boundary, and there are no surface water

4. GROUNDWATER MODEL DEVELOPMENT

bodies in the region large enough to serve as a boundary for a significant portion of the model perimeter.

Therefore, published Indiana Department of Natural Resources (IDNR) groundwater mapping was used to define the limits of the GWMP model. The east and west boundaries of the model were chosen based on published groundwater contours from IDNR (IDNR, 2002). Groundwater flow is perpendicular to these boundaries, which helps to delineate the selection of boundary conditions. For the deeper consolidated aquifers, IDNR published potentiometric surface contours in 1976 (Herring, 1976). This is the only historical information that was found for groundwater heads in the deeper consolidated aquifer at the model boundaries, so constant head boundary conditions for the consolidated aquifer were based on these 1976 contours.

The resulting GWMP model boundary extends from approximately 73rd Street on the north to just south of Interstate 465, and from Raceway Road on the west to Arlington Avenue on the east, as show on Figure 4.1. The horizontal projection chosen for this model is in units of meters, because most of the supporting data and mapping are projected in meters. The model covers approximately 120 square miles beneath the City of Indianapolis. The edges of the model are set at least two (2) miles from the proposed tunnel alignment, which provides adequate separation from the study area to minimize the effect of boundary conditions on the model results near the tunnel.

The model grid cell size is approximately 150 feet by 150 feet along the proposed tunnel alignment and increases to approximately 1,500 feet by 1,500 feet at the edges of the model. Using a 150 feet square grid size, the proposed tunnel corridor will be adequately represented by the model. The model grid was rotated approximately 30 degrees east from north to help align the rows and columns of grid cells with the primary groundwater flow directions based on the IDNR groundwater contours (Figure 4.2).

4. GROUNDWATER MODEL DEVELOPMENT

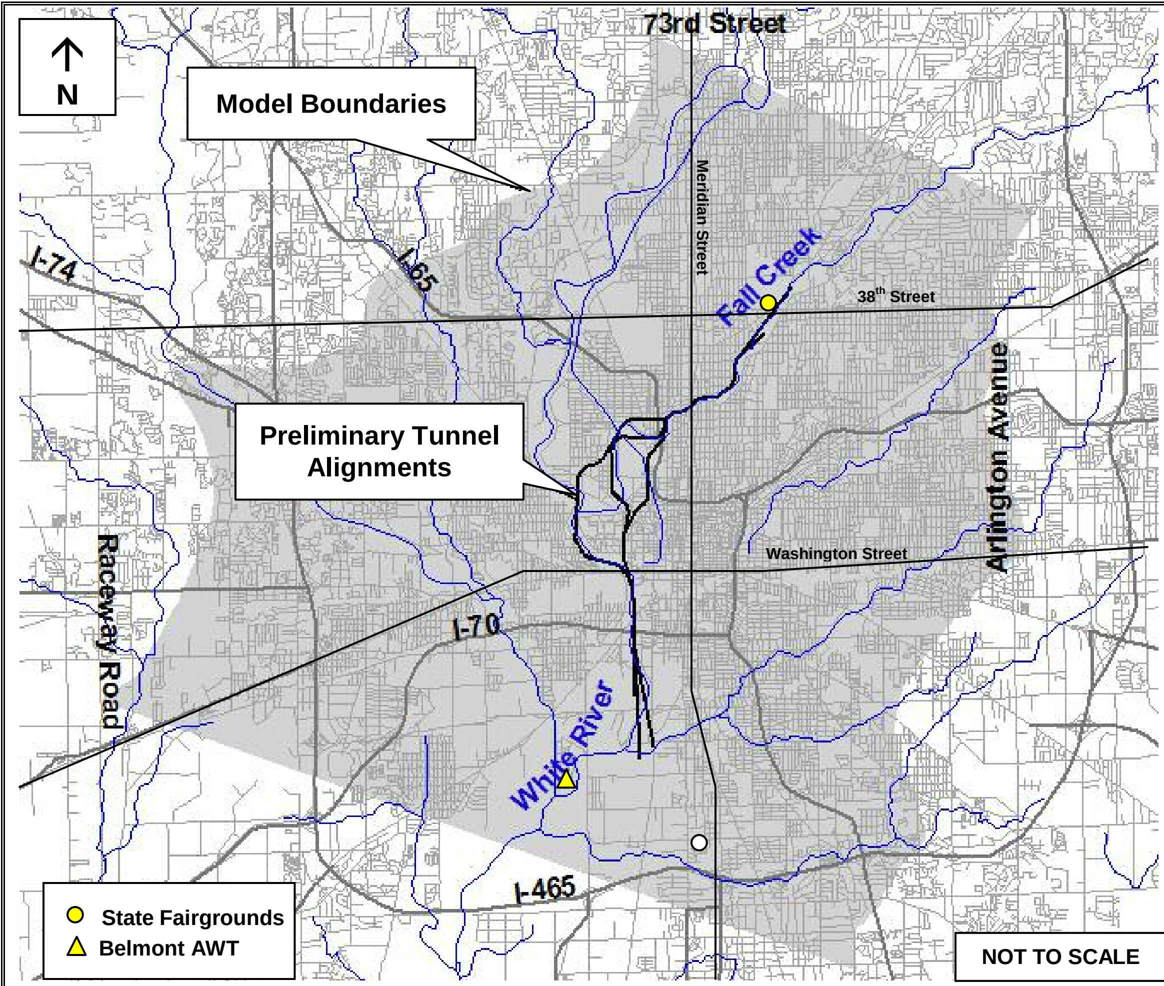

Figure 4.1 Horizontal Boundaries of GWMP Model

4. GROUNDWATER MODEL DEVELOPMENT

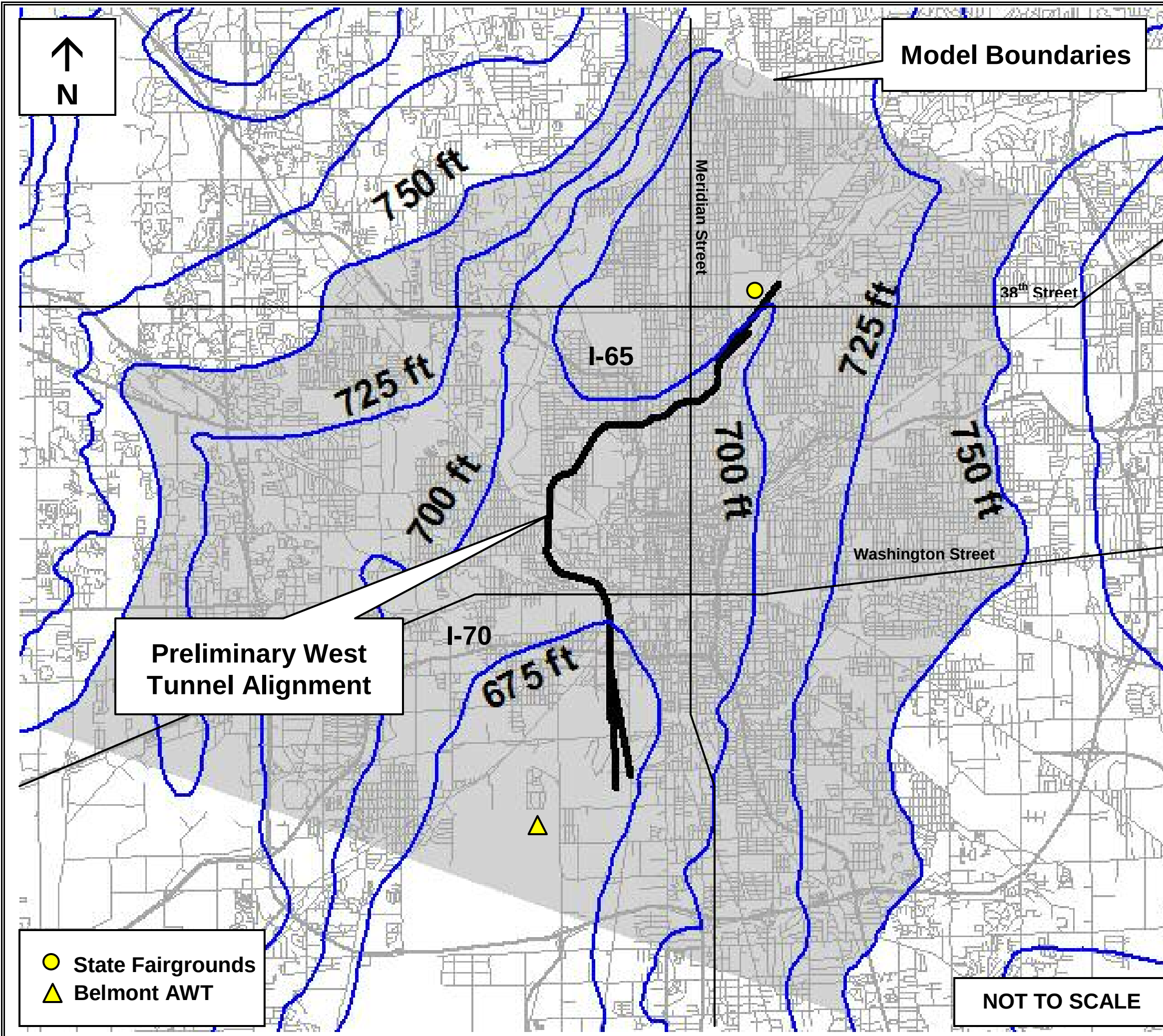

Figure 4.2 Model Boundaries with IDNR Groundwater Contours

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4. GROUNDWATER MODEL DEVELOPMENT

4.3 AQUIFER PARAMETERS

4.3.1 Aquifer Layering and Thickness

The GWMP model was divided into a total of five (5) aquifer layers as described below, summarized in Table 4.1, and illustrated in Figure 4.3.

- Layer 1 – Surficial Aquifer representing the alluvium, outwash and glacial till.
- Layer 2 – Layer that represents the New Albany shale on the southwest end of the model and the top of the carbonate aquifer in direct contact with the surficial aquifer on the north/northeast end of the model.
- Layers 3-5 – Deeper portions of the carbonate aquifer extending to the top of the basal confining unit. The carbonate layer is divided into three (3) sublayers to define the location of the proposed tunnel.
- Basal Confining Unit – This unit is not a defined layer in the model, but it represents the lower confining unit where groundwater flow is assumed not to affect modeling results.

Table 4.1
Conceptual Model Layer Representation

Layer No.	Aquifer Layer	
1	Surficial Aquifer	
2	New Albany Shale (south)	Top of Carbonate Aquifer (north)
3	Carbonate Aquifer Layer above Proposed Tunnel	
4	Carbonate Aquifer Layer in Zone of Proposed Tunnel	
5	Carbonate Aquifer Layer below Proposed Tunnel	
-	Basal Confining Unit (not represented)	

4. GROUNDWATER MODEL DEVELOPMENT

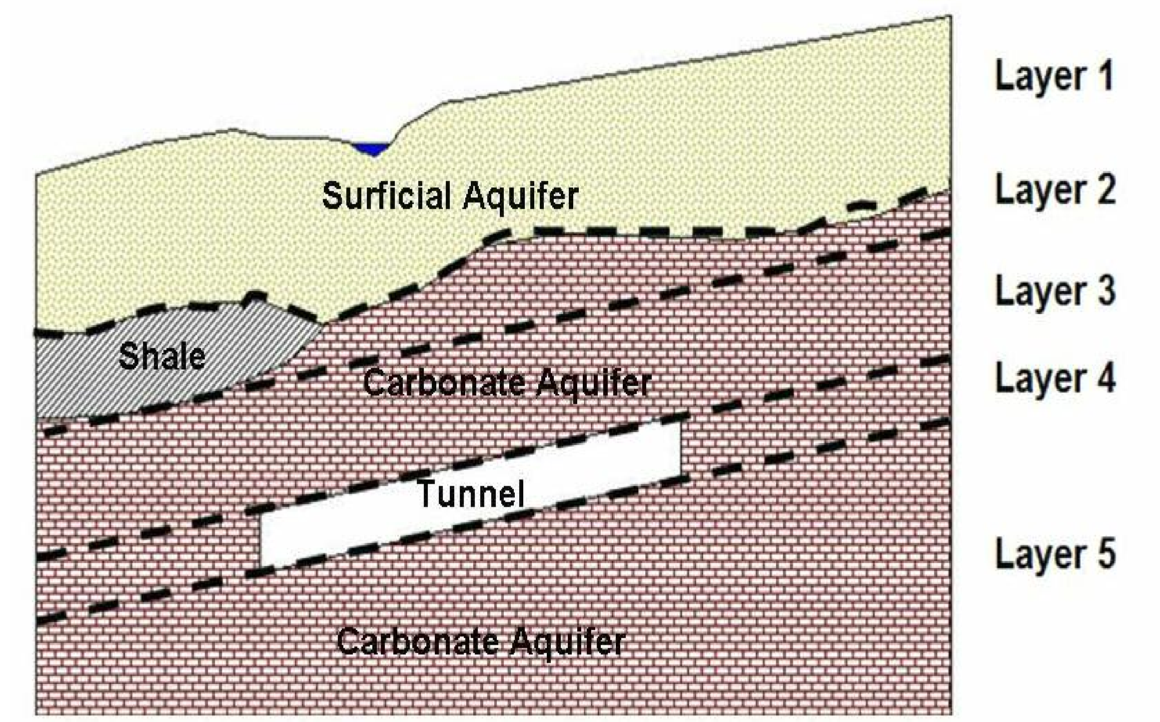

Figure 4.3 Illustration of GWMP Model Vertical Layers

The thicknesses of these aquifer layers were determined from boring logs obtained from IDNR for more than 500 wells across the area (Figure 4.4). Most of these borings are in the surficial aquifer, or extend only partially into the carbonate aquifer. Where data were missing, published information for aquifer thicknesses and digital contour mapping of the carbonate aquifer surface were used to estimate the elevations of the deeper aquifer layers at these boring locations (Casey, 1992; IDNR, 2002; Herring, 1976). Once elevations were established for each aquifer layer at each boring, the borings were imported into GMS and used to create three-dimensional surfaces representing the layer interfaces.

4. GROUNDWATER MODEL DEVELOPMENT

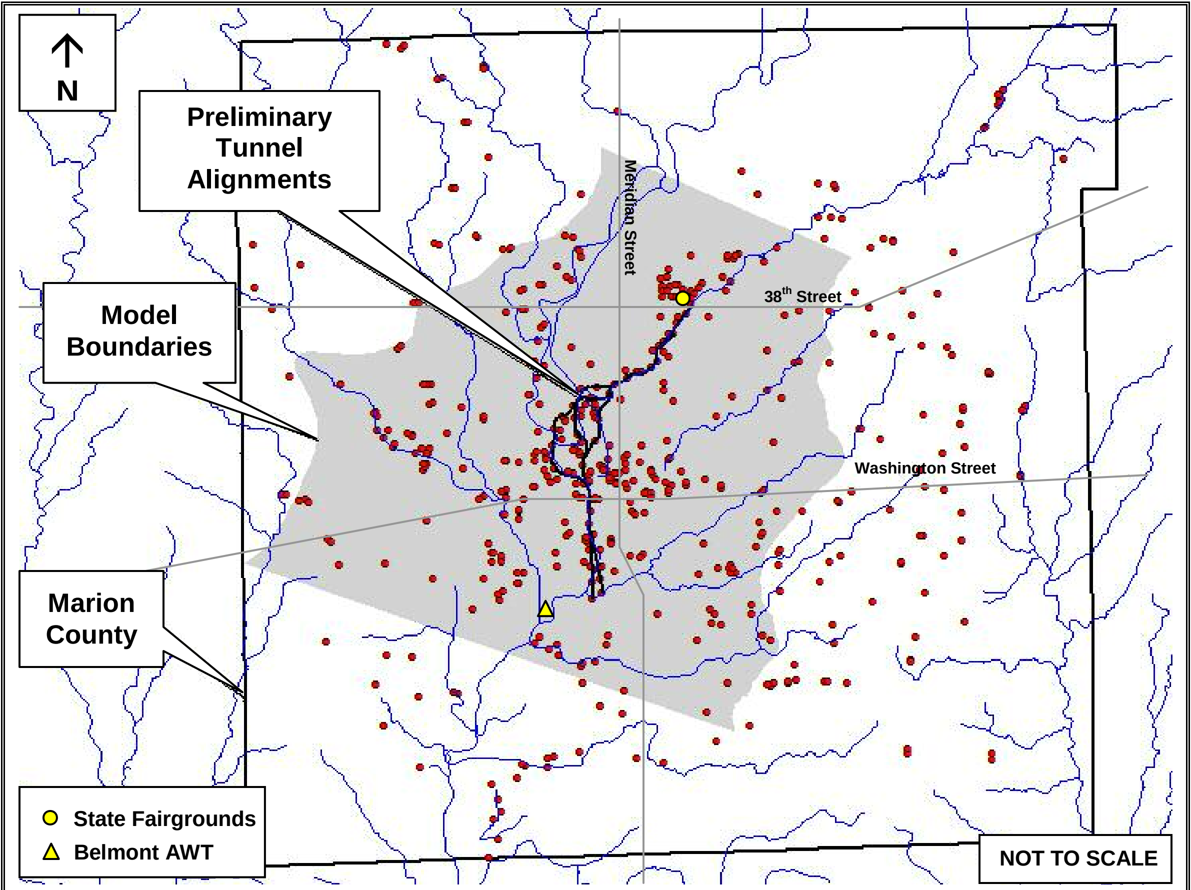

Figure 4.4 Borings Used to Define Aquifer Layer Elevations

4.3.2 Aquifer Hydraulic Characteristics

Because of the regional nature of this project and a focus on the carbonate aquifer, the surficial aquifer (Layer 1) was subdivided into zones of: a) alluvium, b) outwash, and c) glacial till. In general, the alluvium exists along the major streams with the outwash lying along the edges of the alluvium, and the glacial till lying beneath upland areas away from the streams. Figure 4.5 shows the zones of glacial till, outwash, and alluvium used to represent the surficial aquifer. The glacial till is composed of finer-grained material such as silt and clay, and has a lower permeability than the alluvium or outwash. Published reports provided adequate information on the hydraulic properties of the surficial aquifer.

4. GROUNDWATER MODEL DEVELOPMENT

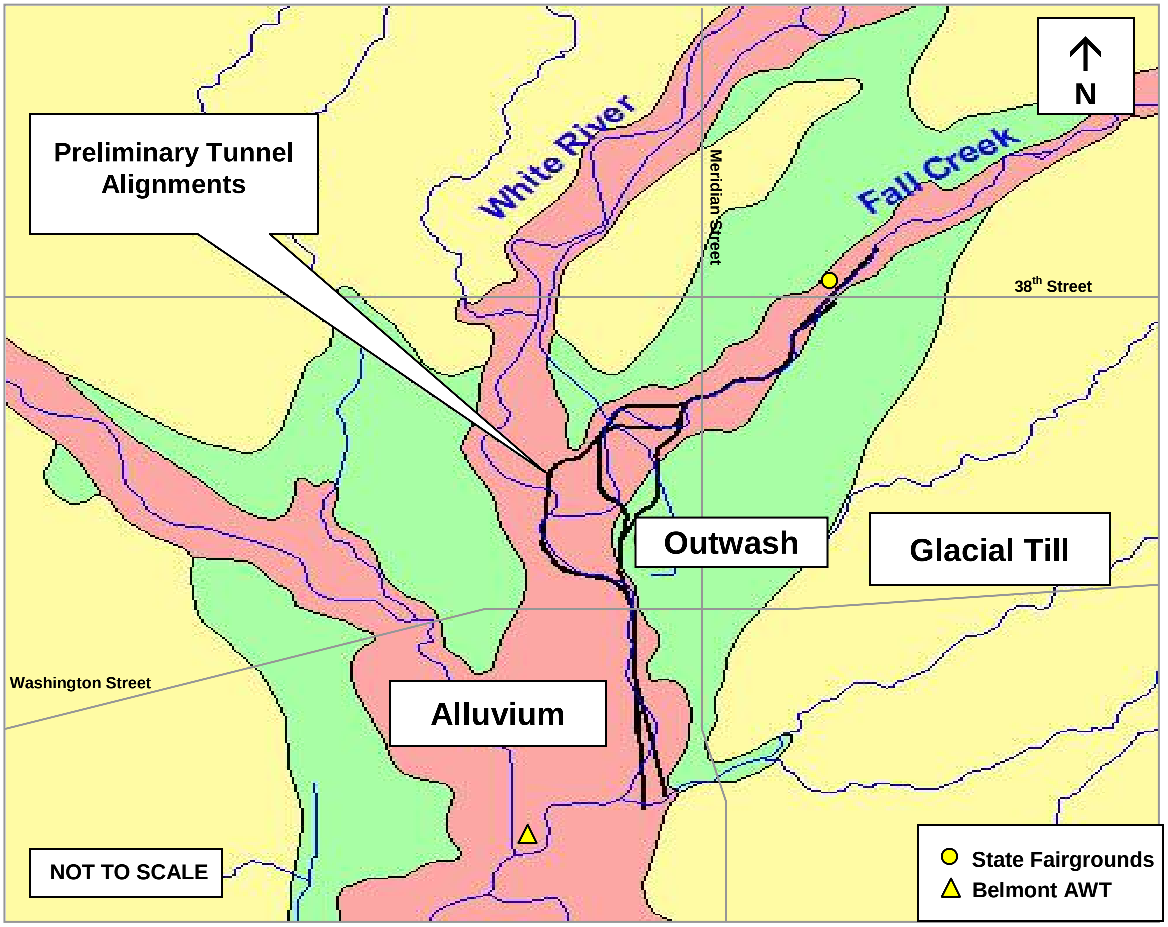

Figure 4.5 Surficial Aquifer Zones

There was limited information available on the hydraulic characteristics of the New Albany shale. However, based on the lack of productive wells in the shale, the hydraulic conductivity of the shale is assumed to be much lower than the alluvium or carbonate. The limits of the New Albany shale are shown on Figure 4.6. For any locations in the southern extents of the model where the shale is overlain by the Borden Group of Mississippian age, it was assumed to be relatively impermeable and was combined with the shale in Layer 2 of the model (IDNR, 2002).

4. GROUNDWATER MODEL DEVELOPMENT

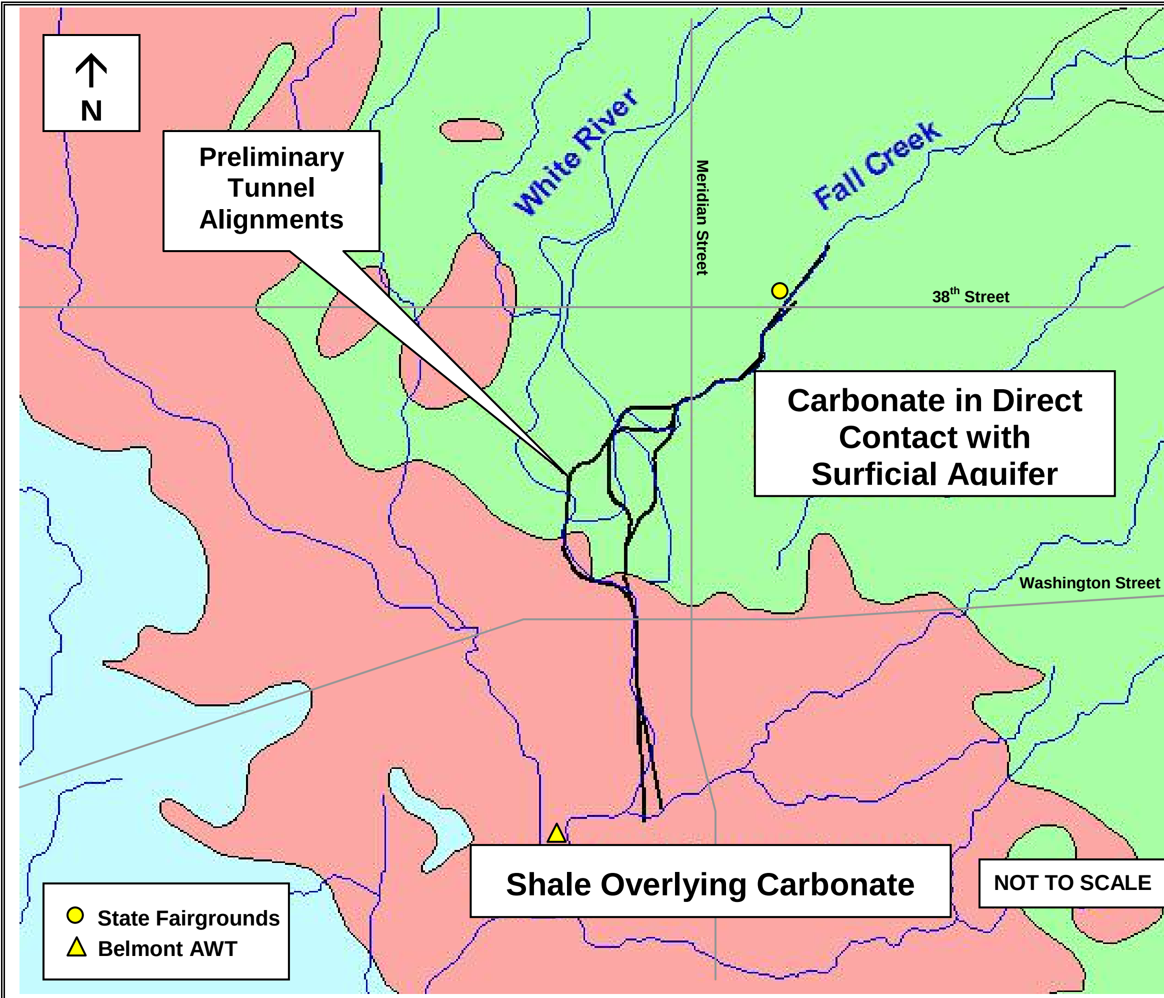

Figure 4.6 Top of Bedrock (Shale and Carbonate) in Contact with Bottom of Surficial Aquifer (Layer 2)

4. GROUNDWATER MODEL DEVELOPMENT

There is also limited information on the hydraulic characteristics of the Silurian-Devonian carbonate aquifer since most wells are screened in the surficial aquifer. Detailed information for the area's largest deep wells drilled into the carbonate aquifer owned by the City of Indianapolis were unavailable for review. Based on available literature and a review of data collected from Phase 1A geotechnical borings, the average hydraulic characteristics of the carbonate aquifer were estimated across the study area.

As described in Section 2, the hydraulic conductivity of the carbonate aquifer is highly variable across short distances, ranging from possibly as much as several hundred feet per day in highly fractured areas to relatively impermeable in other areas. It is reported that the upper 100 feet of the Silurian-Devonian aquifer is the most transmissive (Cable, et.al., 1971). The carbonate represented in model Layers 2, 3, and 4 are generally within this zone. It was also reported that the carbonate experienced less weathering in areas where it is overlain by shale (McGuinness, 1943), therefore it is possible that the hydraulic conductivity of the carbonate in the southern portions of the study area are lower than in the northern portion where the shale is not present. Because it is not possible to predict the locations of the fractures and joints, average hydraulic conductivities were used in the model for the shallow carbonate of Layers 2 and 3. It was determined from Phase 1A geotechnical boring data that the deeper carbonate aquifer of Layers 4 and 5 has a lower hydraulic conductivity than the upper carbonate. This assumption should be validated following future geotechnical and hydrogeologic investigations.

4. GROUNDWATER MODEL DEVELOPMENT

Table 4.2 provides estimates of the various aquifer layers in the study area based on multiple sources of the hydraulic properties.

Table 4.2
Estimated Hydraulic Properties of Aquifer Layers

Source	Aquifer Zone	Transmissivity (gpd/ft)	Assumed Thickness (ft)	Horizontal or Vertical K	K (ft/day)
IDNR, 2002	alluvium	14,690 – 150,560	10 – 150	horizontal	25 – 252
Bugliosi, 1990	alluvium	74,800 – 209,500	80	horizontal	125 – 350
Cable et.al., 1971	alluvium	-	-	horizontal	200 – 334
Meyer, 1978	alluvium	-	-	horizontal	354
USGS/IDNR, 1983	alluvium	-	-	horizontal	200 – 400
Bloyd, 1974	alluvium	-	-	horizontal	267
Bobay, 1988	alluvium	-	-	horizontal	100 – 240
Herring, 1976	alluvium	-	-	horizontal	500 – 700
Black & Veatch, 2003	alluvium	-	-	horizontal	500
Meyer et.al., 1975	outwash	-	-	vertical	24
USGS/IDNR, 1983	outwash	-	-	horizontal	50
IDNR, 2002	till	1,370 – 29,700	0 – 80	horizontal	-
Freeze and Cherry, 1979	till	-	-	horizontal	0.3 (textbook value)
Herring, 1976	till	-	-	vertical	0.003
Meyer et.al., 1975	silt and clay (till)	-	-	vertical	0.0001 – 0.07
Bugliosi, 1990	till	-	-	vertical	0.000007 – 0.07

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4. GROUNDWATER MODEL DEVELOPMENT

Table 4.2 cont.
Estimated Hydraulic Properties of Aquifer Layers

Source	Aquifer Zone	Transmissivity (gpd/ft)	Assumed Thickness (ft)	Horizontal or Vertical K	K (ft/day)
Bobay, 1988	deep sand and gravel	-	-	horizontal	40 – 100
IDNR, 2002	outwash	1,940 – 54,870	20 - 40	horizontal	89
IDNR, 2002	shale	110 – 1,130	50	horizontal	0.3 – 3
Freeze & Cherry, 1979	shale	-	-	horizontal	0.00003 (textbook value)
Casey, 1992	upper carbonate	70 – 28,000	-	Horizontal	0.01 – 500 (highly variable)
Bugliosi, 1992	carbonate	-	-	horizontal	5 – 100
Cable et.al., 1971 Fenelon and Bobay, 1994	upper 100' of carbonate	-	-	horizontal	13.4 (avg, but highly variable)
Black & Veatch, 2003	carbonate	-	-	horizontal	3 – 100 (avg of 15)
Black & Veatch, 2006	deep carbonate	-	-	horizontal	0.0003 – 0.03 (packer tests)
Freeze & Cherry, 1979	limestone/ dolomite	-	-	horizontal	0.03 (textbook value)

Based on values indicated in Table 4.2, the initial hydraulic conductivities assigned to each of the model layers is shown in Table 4.3.

4. GROUNDWATER MODEL DEVELOPMENT

Table 4.3
Average Baseline Hydraulic Conductivities Assigned to Model

Model Layer	Zone within Layer	Horizontal K (ft/day)	Vertical K (ft/day)
1	Alluvium	250	25
	Outwash overlain by till (composite)	10	0.05
	Till	5	0.025
2	Shale	1	0.01
	Carbonate in direct contact with surficial aquifer	15	0.3
3	Carbonate just above zone of tunnel	15	0.3
4	Carbonate in zone of tunnel	1	0.3
5	Deep carbonate below zone of tunnel	1	0.01

4.4 RECHARGE FROM PRECIPITATION

The average annual precipitation in the Indianapolis area is 40.95 inches (NOAA, 2006). It has been estimated that nearly 70 percent of the precipitation that falls in the area is lost to evapotranspiration (ET) (Cable, et.al., 1971). The remaining 30 percent either runs off as surface flow to streams or as subsurface flow that eventually discharges from the aquifer to streams or wells (often referred to as baseflow). The baseflow is an estimate of the net amount of groundwater recharge that occurs from precipitation after other losses are discounted. Previous studies have estimated the amount of groundwater recharge that occurs in the region (Table 4.4). Current and future development may have or will decrease the amount of evapotranspiration and increase the amount of runoff. Estimates of groundwater recharge may decrease in time due to anticipated increases in development.

4. GROUNDWATER MODEL DEVELOPMENT

Table 4.4
Estimates of Groundwater Recharge

Source	Recharge Estimate
Bechert and Heckard, 1966	8 to 16% of precipitation
Cable, et.al., 1971	Approximately 7.15 in/yr, average across the area
Meyer, 1975	13.6 in/yr for outwash; 2 in/yr for glacial till
Gillies, 1976	11.9 in/yr for outwash; 3.7 in/yr for glacial till
Herring, 1976	12.6 in/yr for alluvium; 2.4 to 5.3 in/yr for glacial till
Smith, 1983	12 in/yr for outwash; 4 in/yr for glacial till
Bloyd, 1974	0.31 cfs per square mile (4.2 in/yr average, excluding ET)
Fenelon and Bobay, 1994	2.0 in/yr for glacial till

Based on the estimates of groundwater recharge in Table 4.4, the baseline recharge values applied to the model are as follows:

- Alluvial areas where sand and gravel are near surface = 10 in/yr
- Areas covered by glacial till = 2.0 in/yr

These initial values were subsequently modified during the calibration of the model, as explained later in this report.

4.5 GROUNDWATER INTERACTION WITH RIVERS AND STREAMS

Groundwater typically discharges from the aquifer into the streams in the Indianapolis area. Groundwater seepage into streams is highly uncertain in Marion County, with estimates of 2 to 4 cubic feet per second (cfs) per mile of stream (Smith, 1983). Where the natural system has been altered with the construction of dams and wells, the flow may be reversed in some cases from the streams into the aquifer. The dams can elevate stream stages above groundwater levels and cause streamflows to recharge the aquifer, and wells can lower the groundwater levels below the stream stage and induce streamflow into the aquifer.

4. GROUNDWATER MODEL DEVELOPMENT

Data from the Marion County Flood Insurance Study and United States Geological Survey (USGS) streamgage information were used to input streambed elevations in the model, estimate normal water surface elevations in the streams, and identify the locations of dams on Fall Creek and White River (FEMA, 2005). A comparison was made of the elevations of the streambeds to published groundwater table elevations. Where the groundwater elevations were well below the streambeds, such as Pogues Run and Pleasant Run, the stream was simulated using the Drain Package in MODFLOW. Simulated with the Drain Package, these streams can only remove groundwater from the aquifer if the groundwater elevation rises above the streambed in the model. If the groundwater elevation remains below these streams, then the streams have no effect on the groundwater budget.

All other streams were simulated with the River Package in MODFLOW, which allows both discharge of groundwater to the stream and recharge of streamflow to the aquifer depending on the head differential. The River Package requires a conductance term that governs the hydraulic “communication” between the streams and the aquifer. The conductance is a function of the hydraulic and physical characteristics, and of the streambed sediment. For most groundwater studies, the streambed conductance is uncertain because detailed testing is rarely performed, and it varies over time with the dynamic nature of stream deposition and scour (Walton, 1964). Herring (1976) estimated the streambed infiltration rate for the White River along the proposed tunnel alignment to be 100,000 gpd/acre/ft. Meyer (1979) estimated the streambed permeability to be between 0.07 and 7.2 ft/day. These values were used as a guide for selecting the initial streambed conductances in the GWMP model. Behind dams where streamflow velocities are lower and fine-grained sediment has clogged the streambed (Meyer, 1979), lower values of streambed conductance were applied to the model. The values were subsequently modified during the calibration of the model, as explained later in this report. Figure 4.7 shows the various segments of streams and the low-head dam locations that are simulated by the GWMP model. The removal of Boulevard Dam in Fall Creek is currently in progress, and the GWMP model will require updating at a future time to represent complete removal of the Boulevard Dam.

4. GROUNDWATER MODEL DEVELOPMENT

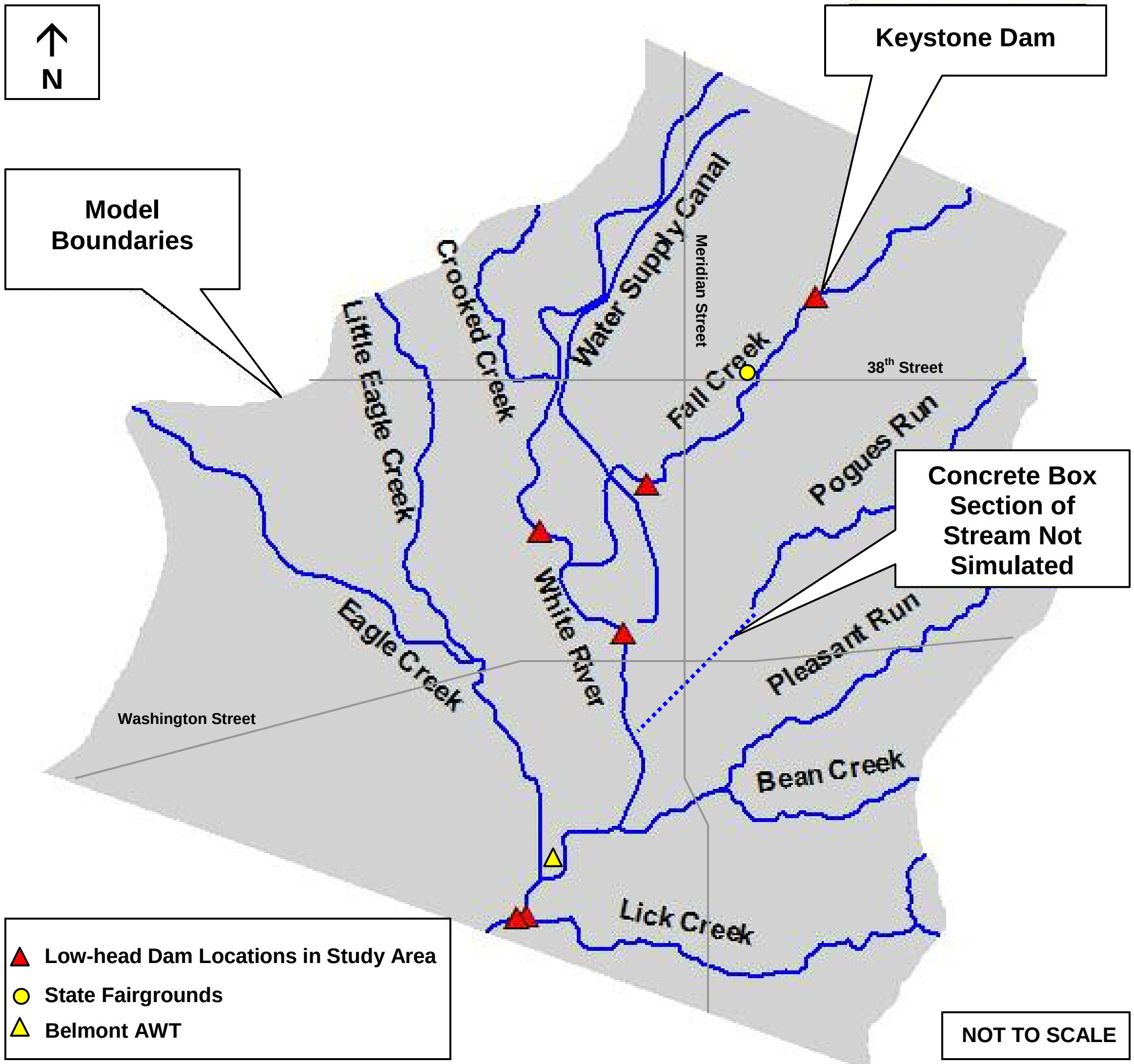

Figure 4.7 Streams Simulated by GWMP Model

4.6 WELLS

Recent production well records were obtained from IDNR for the study area. A total of 126 wells were identified for inclusion in the groundwater model. Of these, there are 103 wells producing groundwater from the surficial aquifer and 23 wells producing groundwater from the carbonate aquifer (Figure 4.8).

4. GROUNDWATER MODEL DEVELOPMENT

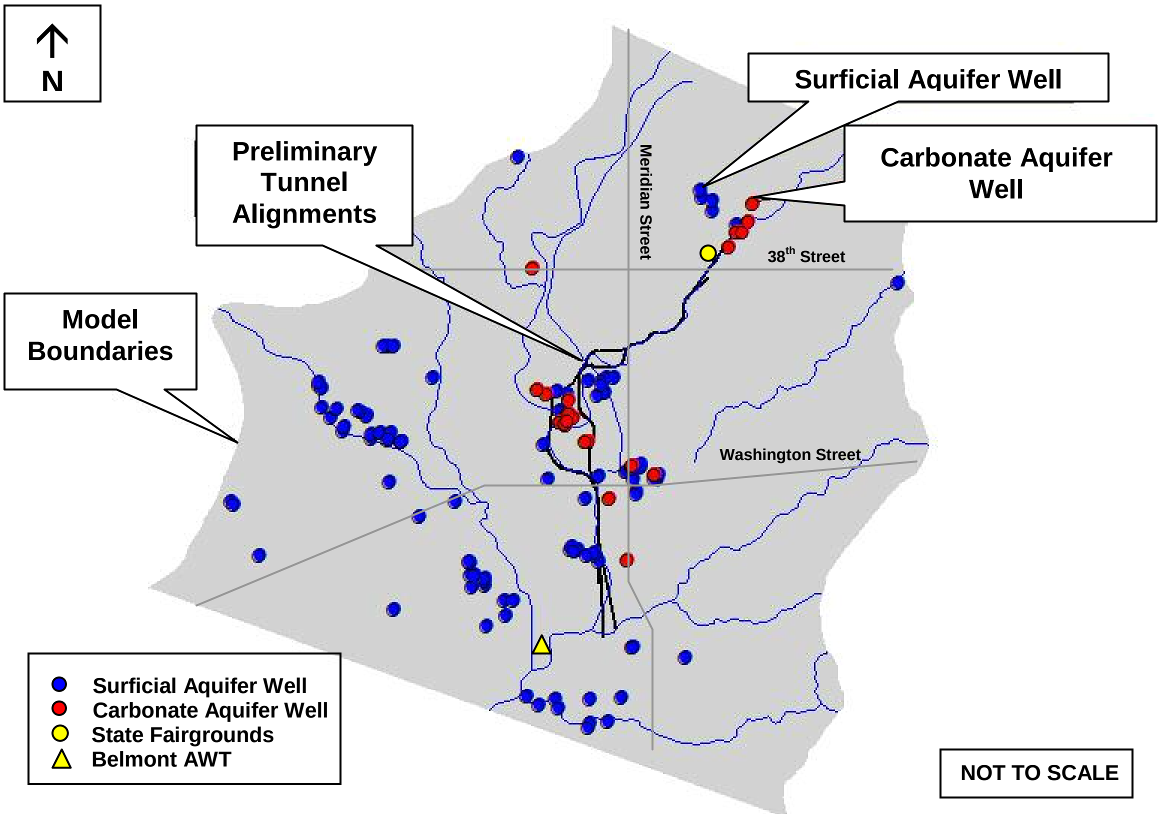

Figure 4.8 Production Wells Simulated in Groundwater Model

Average annual production rates were calculated from IDNR records from 2000 through 2004 for these wells. The total average annual production rates from the surficial aquifer wells and carbonate aquifer wells are 23.8 mgd and 8.9 mgd, respectively. Indianapolis Water's wells at the White River, Riverside, and Fall Creek wellfields account for about 42 percent of the surficial aquifer pumping and about 96 percent of the carbonate aquifer pumping. Although the model only covers approximately 30 percent of Marion County, the modeled pumping rate of 32.7 mgd is approximately 62 percent of the total annual average withdrawal for Marion County. This indicates that most of the pumping in Marion County occurs in the Indianapolis area as represented by this model.

4. GROUNDWATER MODEL DEVELOPMENT

4.7 STEADY-STATE MODELING

Steady-state modeling was performed for this groundwater evaluation. A steady-state model is a representation of the aquifer system as it achieves equilibrium over the long-term with inflows equaling outflows. Steady-state modeling gives an average estimate of groundwater conditions without simulating the intense variations that may occur. The simulation of time-variant aquifer conditions is called a transient groundwater simulation. Transient modeling requires a significant amount of information on the variability in each of the aquifer parameters, such as the following:

- Data is required for the variability in the stage of each of the streams throughout the study area.
- Streambed conductance would be higher in the summer and lower in the winter based on water temperature and viscosity.
- Recharge would vary between the wet season and the dry season.
- Data is required for the variability in pumping rates for all of the wells in the study area.
- Data is required for storability and specific yield to represent the storage properties of each of the aquifer layers.
- Historical groundwater measurements, preferably from a network of nested wells, are needed over a period of time from each of the aquifer layers to be able to calibrate a transient model over time.

Based on the literature review and discussions with IDNR, time-variant historical data is limited for these parameters in the project area. This is especially true for historical groundwater measurements to be able to calibrate and verify a transient model, and for the variability in the stages of the streams that are being simulated by the model. If determined to be necessary for the protection of groundwater resources in Indianapolis, the analysis of transient aquifer conditions can be performed in the future as additional data become available.